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(54) **COMPOSITE DIFFRACTION DEVICE**

(57)   A complex diffraction device, which is excellent in designability, easy in setting the diffraction angle, adaptable to size increase, and easy to handle by adding a diffraction function resulting from an uneven pattern to the diffraction device comprising a liquid crystalline layer where the helical orientation of the smectic liquid crystal phase having a helical structure is maintained.

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Description

[Filed of the Invention]

[0001]   This invention relates to a complex diffraction device, which is applicable to various fields, such as optics, optoelectronics, optical information recording, and liquid crystal display devices and to various uses such as those of security and design, and can be produced so as to have a large area and handled easily.

[Background of the Invention]

[0002]   Diffraction devices or holograms, a type thereof, utilizing a photo-diffraction phenomenon have various functions such as a lens function, a spectrum function, a branching/multiplexing function, and an optical intensity distribution conversion. Due to these functions, they have been widely used in spectroscopic devices, hologram scanners of bar-cord readers and optical pickups of compact disks. Moreover, they have also been used for the purpose of preventing credit cards or various notes from being counterfeited, by utilizing the difficulty in counterfeit and designability of the holograms as well.

[0003]   The diffraction devices are classified according to the shapes thereof into amplitude type diffraction devices and phase type diffraction devices. The amplitude type diffraction devices are those in which a light is allowed to pass through non-light-transmitting parts with a uniform thickness, such as long thin wires, periodically arranged so as to obtain diffracted light. The phase type diffraction devices are further classified into those in which periodic grooves are formed on a surface of a substrate which does not absorb light and refractive index modulation type devices in which regions where the refractive index is periodically varied are formed in a layer with a uniform thickness. Unlike the amplitude type diffraction devices, the phase type diffraction devices can be enhanced in diffraction efficiency because of the absence of a region which does not transmit light. Examples of the phase type diffraction devices each having grooves on its surface are those obtained by forming grooves on a surface of a glass, metal, or plastic. Examples of the refractive index type diffraction device are holograms made using gelatin dichromate or photo polymers.

[0004]   The helical structure of a smectic liquid crystal is also known to function as one of the refractive index type diffraction devices as described in, for example, Jpn. J. Appl. Phys., Vol. 21, page 224, (1982).

[0005]   In the above-mentioned use of preventing credit cards or notes from being counterfeited, a hologram is produced by embossing a thermoplastic film so as to form grooves. However, in the case of seeking more enhanced designability and anti-counterfeit properties, there is a limit for such a hologram. If a light made incident on a diffraction device can be diffracted in a plurality of directions or angles therefrom, the device can be expected to find more extensive uses.

[0006]   The object of the present invention is to provide a complex diffraction device which has a refractive index modulation type diffraction function using the helical structure of a liquid crystalline phase in combination with a diffraction function using grooves formed on its surface, resulting in enhanced designability, and is easy to set diffraction angles and to handle, and adaptable to size increase.

[Disclosure of the Invention]

[0007]   The diffraction device according to the present invention is characterized in that a diffraction function originating from an uneven pattern is imparted to a diffraction device comprising a liquid crystal layer where the helical orientation of a smectic liquid crystalline phase having a helical structure is maintained.

[0008]   The diffraction device according to the present invention has two types of diffraction functions one of which is obtained from the fixed helical orientation of the smectic liquid crystalline phase and the other of which is obtained from an uneven pattern formed on the surface thereof.

[0009]   The smectic liquid crystalline phase of the liquid crystal layer used in the present invention denotes a liquid crystalline phase wherein the liquid crystalline molecules form a smectic layer structure which is one-dimensionally crystal and two-dimensionally liquid.

[0010]   Examples of the smectic liquid crystalline phase are smectic A phase, smectic B phase, smectic C phase, smectic E phase, smectic F phase, smectic G phase, smectic H phase, smectic I phase, smectic J phase, smectic K phase, and smectic L phase. Among these, preferred are those wherein liquid crystalline molecules are aligned in tilting relation to a normal direction of the smectic liquid crystal layer, such as smectic C phase, smectic I phase, smectic F phase, smectic J phase, smectic G phase, smectic K phase, and smectic H phase.

[0011]   Alternatively, in the present invention, there may be suitably used liquid crystalline phases exhibiting optical activity and ferroelectricity such as chiral smectic C phase (SmC*), chiral smectic I phase (SmI*), and chiral smectic F phase (SmF*), liquid crystalline phases exhibiting optical activity and antiferroelectricity such as chiral smectic C_A phase (SmC$_A$*), chiral smectic I_A phase (SmI$_A$*), and chiral smectic F_A phase (SmF$_A$*), and liquid crystalline phases

exhibiting optical activity and ferrielectricity such as chiral smectic C_γ phase (Sm C_γ^*), chiral smectic I_γ phase (Sm I_γ^*), and chiral smectic F_γ phase (Sm F_γ^*).

[0012]　Further alternatively, there may be suitably used those which are chiral and exhibit a smectic phase having a helical structure as described in J. Matter. Chem. Vol. 6, page 1231 published in 1996 or J. Matter. Chem. Vol. 7, page 1307 published in 1997.

[0013]　However, with the objective of easy synthesis of liquid crystalline materials, easy orientation of the helical structure in the smectic liquid crystalline phase, easy variation of the helical pitches, and stability of the helical structure, the most preferred is chiral smectic C phase or chiral smectic C_A phase.

[0014]　The term "helical structure in the smectic liquid crystalline phase" used herein denotes a structure wherein the longitudinal axes of the liquid crystalline molecules tilt at a certain angle from the vertical direction of each smectic layer, and the tilt directions twist little by little from one layer to another. The center axis of the helix in this helical structure is referred to as "helical axis", while the length in the helical axis direction for one helical turn is referred to as "helical pitch".

[0015]　When a light is allowed to pass through a liquid crystal layer comprising a helical-structured smectic liquid crystalline phase, the diffraction direction of the light depends on the helical axes direction of the liquid crystalline phase. For example, in the case where the helical axes are parallel to the liquid crystal layer, a light made incident vertically thereto is diffracted to the helical axes direction. No particular limitation is imposed on the helical axes direction of the liquid crystal layer forming the complex diffraction device of the present invention. Therefore, the helical axes direction may be properly selected such that the desired characteristics can be exhibited. For example, the helical axes direction may be parallel to or tilted with respect to the liquid crystal layer surface. Furthermore, the tilt angle may be varied discretely or continuously. Moreover, the helical axes direction may be microscopically determined by the domain and may be macroscopically directed to various directions or to the same direction. The helical structure is not necessarily formed entirely in the liquid crystal layer and thus may be formed on the surface area or interior of the liquid crystal layer, or a part thereof.

[0016]　The helical pitch in the liquid crystal layer is usually from 0.1 to 20 μm, preferably 0.2 to 15 μm, and more preferably 0.3 to 10 μm. The helical pitches may be constant in the liquid crystal layer, but may be varied depending on positions therein. The variation may be continuously or discretely. The helical pitches can be properly adjusted in a conventional manner, for example, by adjusting the orientation conditions such as temperature, the optical purity of the optically active portion, and the blend ratio of the optical active materials. The helical pitches correspond to the grating pitches. When a light is allowed to be made incident to the helical structure, a diffraction at angles corresponding to the helical pitches occurs. Therefore, it is necessary to properly adjust the helical pitches in order to obtain the desired diffraction angle.

[0017]　In the complex diffraction device according to the present invention, the liquid crystal layer having diffractivity originating from its helical structure is provided on its surface with an uneven pattern. The may be in any shape as long as it can exhibit a diffraction resulting therefrom. For example, it may have a rectangular groove-, corrugate-, saw tooth- or step-like shape formed on a flat surface at the same interval. Alternatively, the pattern may be the combination of two or more types of these uneven patterns. Further alternatively, the pattern may be designed by mixing a portion having an uneven pattern and a portion which is free thereof, or forming a region where the light is diffracted in different directions such that markings, patterns or logos emerge by diffraction.

[0018]　Since the period or intervals of the uneven pattern corresponds to the grating pitches, the desired angle of diffraction can be obtained by adjusting properly the period or intervals.

[0019]　The complex diffraction device may be those obtained by forming a layer having an uneven pattern and then laminating the layer on the liquid crystal layer, or by forming an uneven pattern directly thereon. In the latter case, the uneven pattern may be formed on one side or both sides of the liquid crystal layer surfaces.

[0020]　In the present invention, the diffraction direction and/or angle of the liquid crystal layer may be the same as or different from those resulting from the uneven pattern. However, when consideration is given to the effects or designability of the complex diffraction device, it is preferred that the direction and/or angle of the diffraction resulting from the helical structure are partially different from those resulting from the uneven pattern.

[0021]　In the liquid crystal layer forming the inventive complex diffraction device, the helical structure of the smectic liquid crystalline phase must be maintained. "Maintaining the helical structure" means that the change in the helical structure with time does not occur under the conditions where the liquid crystal layer is functioned as the complex diffraction device. One of the methods of maintaining the helical structure is to sandwich the liquid crystal layer with a pair of alignment substrates. In this method, if either one of the substrates are removed, there is a possibility that the helical structure can not be maintained in a stable state.

[0022]　Another method is to fix the helical structure of the liquid crystalline phase. This method is preferred to the above-mentioned method in terms of easy production of the liquid crystal layer, heat-resistance, and practical use.

[0023]　The methods of fixing the helical structure in the liquid crystalline phase are roughly classified into a glass fixing method and a polymerization fixing method. The glass fixing method is that in which the helical structure is fixed

by transferring the smectic liquid crystalline phase to a glass state. Eligible liquid crystalline materials for this method are those, hereinafter referred to as "liquid crystalline material A", which can form the smectic liquid crystalline phase having a helical structure and can be in a glass state by cooling. The polymerization fixing method is that in which the smectic liquid crystalline phase having a helical structure is fixed by polymerizing or cross-linking liquid crystalline molecules. Eligible liquid crystalline materials for this method are those, hereinafter referred to as "liquid crystalline material B", which can form the smectic liquid crystalline phase having a helical structure and can be polymerized or cross-linked with light, electron beam, or heat.

[0024] More specific examples of eligible liquid crystalline materials for the liquid crystal layer are any of low-molecular weight liquid crystals and liquid crystalline polymers which are capable of forming the helical-structured smectic liquid crystalline phase. The liquid crystals only need to be those exhibiting the desired liquid crystallinity and orientation and may be a mixture of a single or plurality types of low molecule weight- and/or liquid crystalline polymer materials and a single or plurality types of low molecule weight- and/or non-liquid crystalline polymer materials.

[0025] Eligible low molecular weight liquid crystals are Schiff base compounds, biphenyl compounds, terphenyl compounds, ester compounds, thioester compounds, stillbene compounds, tolan compounds, azoxy compounds, phenyl cyclohexane compounds, pyrimidine compounds, cyclohexylcyclohexane compounds, and mixtures thereof.

[0026] The liquid crystalline polymers can be classified into main chain type- and side chain type- liquid crystalline polymers. Both of them are eligible for the liquid crystalline materials forming the liquid crystal layer of the present invention.

[0027] Examples of the main chain type liquid crystalline polymer are polyester-, polyamide-, polycarbonate-, polyimide-, polyurethane-, polybenzoimidazole-, polybenzoxazole-, polybenzothiazole-, polyazomethine-, polyesteramide-, polyestercarbonate-, and polyesterimide-based liquid crystalline polymers. Among these, particularly preferred are semi-aromatic polyester-based liquid crystalline polymers wherein mesogen providing liquid crystallinity is alternately bonded to a flexible chain, such as polymethylene, polyethyleneoxide, and polysiloxane and wholly aromatic polyester-based liquid crystals which are free of flexible chain.

[0028] Examples of the side chain type liquid crystalline polymers are those having a straight- or cyclic- main chain and a mesogen at each side, such as polyacrylate-, polymethacrylate, polyvinyl-, polysiloxane-, polyether-, polymalonate-, and polyester-based liquid crystals. Among these, particularly preferred are those wherein a mesogen providing liquid crystallinity is bonded to the main-chain via a spacer comprised of a flexible chain and those having a molecular structure wherein the main chain and the side chain both have a mesogen.

[0029] The liquid crystalline material referred herein includes those obtained by blending a chiral dopant with or introducing an optically active unit to the above-described low molecular weight and/or liquid crystalline polymers. For example, such liquid crystalline materials can be obtained by blending a chiral dopant with or introducing an optically active unit to a liquid crystalline material exhibiting smectic C phase, smectic I phase, or smectic F phase. The resulting liquid crystalline material exhibits a chiral smectic liquid crystalline phase which is easy to be aligned in a helical structure, like chiral smectic C phase, chiral smectic I phase, or chiral smectic F phase.

[0030] As described above, the helical pitch and diffraction angle of the inventive complex diffraction device can be adjusted by properly adjusting the amount of the chiral dopant, the introducing ratio of the optically active unit, the optical purity, and the temperature conditions under which a smectic liquid crystalline phase is formed. Whether a helical structure is a right-handed helix or a left-handed helix depends on the chilarlity of the chiral dopant or optically active groups to be used. Therefore, either of the helical structure having a right-handed helix or a left-handed helix can be obtained by selecting the chilarlity.

[0031] Among the above-described liquid crystalline materials, suitable for the liquid crystalline material A are the liquid crystalline polymers. Suitable for the liquid crystalline material B are those having a functional group responding to light, electron beam, or heat. Examples of such a functional group are vinyl, acryl, methacryl, vinylether, cinnamoyl, aryl, acetylenyl, crotonyl, aziridinyl, epoxy, isocyanate, thioisocyanate, amino, hydroxyl, mercapto, carboxyl, acyl, halocarbonyl, aldehyde, sulfonic acid, and silanol groups. Among these, preferred are acryl, methacryl, vinyl, vinylether, cinnamoyl, epoxy, and aziridinyl groups. Particularly preferred are acryl, methacryl, vinyl, vinylether, cinnamoyl, and epoxy groups.

[0032] These functional groups only needs to be contained in the liquid crystalline material and thus may be contained in the liquid crystalline material, non-liquid crystalline material, or one or more additives hereinafter described. In the case where the functional groups are contained in each of two or more types of materials, these functional groups may be the same or different. Furthermore, in the case where two or more functional groups are contained in one of the materials, they may be the same or different.

[0033] If necessary, when producing the liquid crystal layer of the inventive complex device, additives such as surfactants, polymerization initiators, polymerization inhibitors, sensitizers, stabilizers, catalysts, dyes, pigments, ultraviolet absorbers, and adhesion improvers may be blended in an amount of 50 percent by mass or less, preferably 30 percent by mass or less, and more preferably 10 percent by mass or less, based on the total mass.

[0034] The liquid crystal layer of the inventive complex device can be produced by developing the liquid crystalline

material, if necessary, together with the additives and maintaining a helical structure.

[0035] No particular limitation is imposed on two interfaces on both sides of the liquid crystalline material upon developing, which interfaces, therefore, may be gaseous phase-, liquid phase- or solid phase-interfaces and not need to be the same. However, with the objective of easy production of the liquid crystal layer, it is recommended to employ two interfaces both of which are solid or one of which is solid and the other of which is gaseous.

[0036] Examples of the gaseous phase interface are air- and nitrogen-interface. Examples of the liquid phase interface are water, organic solvents, liquefied metals, other liquid crystals, and melted polymeric compounds. Examples of the solid phase interface are plastic film substrates comprised of polyimide, polyamideimide, polyamide, polyetherimide, polyether ether ketone, polyether ketone, polyketone sulfide, polyether sulfone, polysulfone, polyphenylene sulfide, polyphenylene oxide, polyethylene terephthalate, polybutylene terephthalate, polyethylene naphthalate, polyacetal, polycarbonate, polyallylate, acrylic resins, methacrylic resins, polyvinyl alcohol, polyethylene, polypropylene, poly-4-methylpentene-1 resin, and cellulose-based plastics such as triacetyl cellulose, epoxy resins, polyphenol resins, and liquid crystalline polymers; metal substrates such as aluminum, iron and copper; glass substrates such as blue glass sheet, alkaline glass, non-alkaline glass, borosilicate glass, flint glass and quarts glass; ceramic substrates; and various semi-conductor substrates such as silicon wafers. Eligible solid phase interfaces are also those obtained by forming a film which may be an organic film comprised of polyimide, polyamide, or polyvinyl alcohol, an obliquely deposited film of silicon dioxide or the like, or a transparent electrode of ITO (indium-tin oxide), or obtaining by depositing or sputtering a metal film of gold, aluminum or copper, on the above-described substrates. Furthermore, another eligible solid phase interfaces are thin film transistors (TFT) of amorphous silicon.

[0037] These various substrates may be subjected to an alignment treatment if necessary. In the case of using such substrates, the direction of the helical axes in the resulting liquid crystal layer can be settled in one direction which is determined by the direction of the alignment of the substrates. Depending on the type of liquid crystalline material and solid phase interface and the method of aligning, the direction of the helical axes does not always coincide with the alignment direction of the substrates and may be shifted therefrom. The complex diffraction device of the present invention even if containing such a liquid crystal layer can still perform the effects of the complex diffraction device. Furthermore, in the present invention, it is possible to obtain a complex diffraction device wherein the direction of the helical axes is fixed in one pattern, by altering the aligning direction partially. In the case of using such a method, it is possible to obtain a complex diffraction device which can exhibit a complex diffraction effect caused by the smectic liquid crystal having a helical structure as well as a diffraction effect resulting from the diffraction pattern, for example, by arranging the pattern of regions wherein the helical axes directions are different periodically to an extent that the interference of light occurs.

[0038] In the case of not subjecting the substrates to an alignment treatment, the resulting liquid crystal layer possibly assumes a multi-domain layer wherein the helical axes directions in each domain are random. However, even such a liquid crystalline phase can provide the resulting device with the effects as the complex diffraction device.

[0039] No particular limitation is imposed on the alignment treatment subjected to the various substrates. Examples of the alignment treatment are rubbing, oblique depositing, microgrooving, polymer film drawing, LB (Langmuir-Blodgett) filming, transferring, photo irradiating (photo isomerization, photo polymerization, and photo decomposition), and peeling methods. Particularly with the objective of simplified production process, preferred are rubbing and photo irradiation methods.

[0040] Furthermore, even in the case of using the various substrates as the solid phase interfaces, which have not been subjected to an alignment treatment, it is possible to obtain the liquid crystal layer with the helical axes directions regulated in a certain direction, by applying magnetic or electric field or shear stress to the liquid crystalline material developed between the interfaces; fluidizing or drawing the liquid crystalline material; or subjecting the same to temperature gradient.

[0041] No particular limitation is imposed on the method of developing the liquid crystalline material between the above-described interfaces. Therefore, any suitable methods known in the field can be employed. For example, in the case of developing the liquid crystalline material between two substrates, the liquid crystalline material is injected into a cell formed with these substrates. Alternatively, there may be employed a method in which the liquid crystalline material is laminated with the substrates.

[0042] In the case of using one substrate and a gaseous interface, the liquid crystalline material can be developed by coating it directly on the substrate or dissolving it in a suitable solvent before coating. In the present invention, with the objective of simplified production processes, it is preferred to coat the liquid crystal after being dissolved in a solvent.

[0043] A suitable solvent for this purpose can be selected in accordance with the type of liquid crystalline material and the composition thereof. Generally, the examples of the solvent are halogenated hydrocarbons such as chloroform, hydrocarbons such as chloroform, dichloromethane, carbon tetrachloride, dichloroethane, tetrachloroethane, trichloroethylene, tetrachloroethylene, chlorobenzene, and orthodichlorobenzene, phenols such as phenol and parachlorophenol, aromatic hydrocarbons such as benzene, toluene, xylene, methoxybenzene, and 1,2-dimethoxybenzene, alcohols such as isopropyl alcohol and tert-butylalcohol, glycols such as glycerin, ethylene glycol, and triethylene glycol,

glycol ethers such as ethylene glycol monomethylether, diethylene glycol dimethylether, ethyl cellosolve and butyl cellosolve, acetone, methylethyl ketone, ethyl acetate, 2-pyrrolidone, N-methyl-2-pyrrolidone, pyridine, triethylamine, tetrahydrofuran, diemthylformamide, dimethylacetoamide, dimethylsulfoxide, acetonitrile, butyronitrile, carbon disulfied, and mixtures thereof. If necessary, surfactants or the like may be added to the solvent so as to adjust the surface tension and improve the coatability.

[0044]   It is necessary to adjust the concentration of the liquid crystalline material in the solution depending on the type of liquid crystalline material, solubility thereof, and the film thickness of the final liquid crystal layer. However, it is within the range of usually 3 to 50 percent by mass, and preferably 5 to 30 percent by mass.

[0045]   No particular limitation is imposed on the method of coating the solution. There may be used spin-coat, roll-coat, print, dip, curtain-coat, wire bar coat, doctor blade, knife coat, die coat, gravure coat, micro gravure coat, offset gravure coat, lip coat, and spray coat methods. After coating, the solvent may be dried out if necessary.

[0046]   After the liquid crystalline material which can exhibit the helical structured smectic liquid crystalline phase is developed between the various interfaces by the above-described method so as to be formed into a uniform layer, the inventive complex diffraction device can be obtained by forming the liquid crystalline material so as to assume the helical orientation in the desired helical-structured smectic liquid crystalline phase. No particular limitation is imposed on the method of forming the liquid crystalline material so as to assume the helical orientation in the smectic liquid crystalline phase. There may be suitably employed a method depending on the type of liquid crystalline material. For example, in the case of developing the liquid crystalline material at a temperature at which the material can be formed so as to assume the helical structured smectic liquid crystalline phase, the helical structured smectic liquid crystalline phase may be obtained at the same time. The developed liquid crystalline material is once heated at a temperature higher than that at which the helical structured smectic liquid crystalline phase appears, such that a smectic A phase, a chiral nematic phase or an isotropic phase appears, and after a certain period of time it is oriented so as to assume the helical structure by cooling to a temperature at which a smectic liquid crystalline phase appears.

[0047]   After the helical structured smectic liquid crystalline phase appears in the liquid crystal layer by any of the above-described methods, the helical structure of the smectic liquid crystalline phase is fixed by any suitable method selected depending on the type and composition of liquid crystalline material. In order to fix the helical structure, it is preferred to use the above-described glass fixing method or polymerization fixing method.

[0048]   In the case of using the glass fixing method, the helical structured smectic liquid crystalline phase which appears at a temperature higher than the glass transition temperature of the liquid crystalline material A is fixed by cooling the liquid crystal layer to a temperature at which the liquid crystalline material A is in a glass state. The cooling may be natural cooling or forced cooling.

[0049]   In the case of using the polymerization fixing method, the helical structured smectic liquid crystalline phase which appears when the liquid crystalline material B is in a liquid crystalline state is fixed by polymerizing or cross-linking the liquid crystalline material B. The method of polymerizing or cross-linking may be thermal polymerization, photo polymerization, radiation polymerization of γ ray or the like, electron beam polymerization, polycondensation, or polyaddition. Among these, preferred are photo polymerization and electron beam polymerization because they are easy to control.

[0050]   The liquid crystal layer fixed by the foregoing method is free from disorder in orientation even after removing the substrate and can be used as a complex diffraction device wherein the helical orientation is fixed. The film thickness of the resulting liquid crystal layer is within the range of generally 0.1 to 100 μm, preferably 0.2 to 50 μm, and more preferably 0.3 to 20 μm, with the objective of orientability and productivity.

[0051]   In the present invention, the liquid crystal layer described above is provided with a diffraction function originating form the uneven patterns and recesses formed thereon. The diffraction function may be provided on the liquid crystal layer with the substrate or after removing the substrate. Alternatively, the resulting liquid crystal layer is transferred to another substrate and an uneven pattern is formed on the layer with the substrate. Further alternatively, a plurality of the liquid crystal layers having the same or different diffraction properties are laminated, and the diffraction function originating from an uneven pattern is provided thereon.

[0052]   Examples of the substrate are plastic substrates formed from polyimide, polyamideimide, polyamide, polyetherimide, polyether ether ketone, polyether ketone, polyketone sulfide, polyether sulfone, polysulfone, polyphenylene sulfide, polyphenylene oxide, polyethylene terephthalate, polybutylene terephthalate, polyethylene naphthalate, polyacetal, polycarbonate, polyallylate, acrylic resins, methacrylic resins, polyvinyl alcohol, polyethylene, polypropylene, poly-4-methylpentene-1 resin and cellulose-based plastics such as triacetyl cellulose, epoxy resins, and polyphenol resins; glass substrates; ceramic substrates; papers; and metal substrates. Furthermore, eligible substrates are optical elements such as polarizing plates, retardation plates, and reflecting plates, scattering films, and various liquid crystalline films such as nematic films and cholesteric films.

[0053]   No particular limitation is imposed on the method of providing an uneven pattern. There may be employed a method in which another layer having a diffraction function originating from an uneven pattern is laminated over the liquid crystal layer of the present invention or a method in which a diffraction pattern is provided by forming an uneven

pattern directly on the surface of the liquid crystal layer. Examples of the layer having a diffraction function are plastic films or glass substrates having a diffraction function.

[0054] The method of forming an uneven pattern may be exemplified by a method in which projections and recesses are formed on the liquid crystal surface with an etching technique, or an embossing processing in which a mold having a form of diffraction gratings hereinafter referred to as "embossed plate" is pressed on the liquid crystal layer with a press machine or in which a film having a form of diffraction gratings hereinafter referred to as "embossed film" is laminated over the liquid crystal layer using a laminate machine or the like so as to transfer the diffraction gratings on the liquid crystal layer. In the present invention, it is preferred to provide a diffraction function originating from an uneven pattern by subjecting the liquid crystal layer surface to the embossing processing.

[0055] No particular limitation is imposed on the embossed plate and film. Most of the embossed plates are structures formed from metals or resins and having diffraction gratings. The embossed film may be a film obtained by forming diffraction gratings on a surface of a free-standing film or a laminate of a self-supportive film and a layer with diffraction gratings.

[0056] After the embossing processing, mostly the embossed plate or film is peeled off from the film or substrate containing the liquid crystal layer. However, in the case of using the embossed film, it is possible to use the liquid crystal layer with the film pressed as a laminate.

[0057] At a temperature at which the embossing processing is carried out, the liquid crystal layer must have a fluidity within a suitable range. The temperature for the embossing processing can not be determined with certainty since it depends on the thermal characteristics of the liquid crystal layer such as the glass transition temperature (Tg) and the degree of cross-linking, the substrate of the liquid crystal layer, the type of embossed plate or film , or the method of embossing transfer. However, the embossing processing is carried out from room temperature to 300 °C, preferably room temperature to 200 °C. That is, it is requisites that the disorder in the helical orientation state of the liquid crystal layer hardly occurs at the temperature of the embossing transfer during the period thereof without losing the effects achieved by the present invention after the embossing transfer. It is also requisites to be able to effect the embossing processing efficiently if selecting proper conditions for the embossing transfer and obtain an emboss-processed liquid crystal layer with the effects of the present invention.

[0058] Although it is extremely difficult to describe such a temperature range quantitatively and is impossible to specify it with a single physical quantity, the glass transition temperature (Tg) of the liquid crystal layer after the orientation may be used as an index. In the case of using a liquid crystalline polymer or oligomer as the liquid crystalline material used in the present invention, the glass transition temperature exists in most of the polymers or oligomers. When the fluidity of such polymers or oligomers is measured with increasing the temperature thereof, it is known that the fluidity is gradually increased from a poor state resulting from the glass fixing once the temperature reaches around the glass transition temperature. Therefore, in the case of using a polymer or oligomer wherein the glass transition temperature exists, the embossing processing can be applied to the liquid crystal layer whose glass transition temperature is within range of from room temperature to 200°C after the orientation. If the glass transition temperature is room temperature or less, the fluidity upon the embossing processing becomes too high and thus orientation disorder is prone to occur. If the glass transition temperature is in excess of 200 °C, it becomes difficult to effect the emboss processing in the usual manner adequately to provide the effects achieved by the present invention.

[0059] The resulting emboss-processed liquid crystal layer may be put in use as it is, but may be further cured by light irradiation or thermal cross-linking with the objective of reliability in terms of temperature, humidity, and solvents, and mechanical strength. In the case of using a light cross-linkable liquid crystalline composition and fixing it by the method for the liquid crystalline material B, there may be used a method in which after the orientation is fixed to a certain extent by light irradiation once after the orientation is formed, the diffraction grating is formed, followed by another light irradiation so as to cure the liquid crystal layer.

[0060] The complex diffraction device of the present invention may be provided on its surface with a protective layer formed of the above-mentioned transparent plastic film of a hard coat layer for the purpose of protecting the surface, increasing the strength, and enhancing the environmental reliability.

[0061] The complex diffraction device can be used in various purposes, for example, as light pickups of CDs, DVDs or magneto-optical disks, or optical elements for improving the viewing angle or the brightness of liquid crystal displays; designable films utilizing rainbow coloration caused by diffraction; optical information recording devices; anti-counterfeit security films for credit cards or notes; and combiner for head-up displays.

[Applicability in the Industry]

[0062] The complex diffraction device of the present invention comprises a liquid crystal layer with the helical orientation of a helical structured smectic liquid crystalline phase maintained, and is further provided with a diffraction function resulting from an uneven pattern formed on the layer. Therefore, the inventive device has an effect of diffraction in a plurality of directions or angles. Furthermore, the inventive device can be built in another optical system because it is

adaptable to large size, and is light, low in manufacturing cost, and easy to handle. Therefore, the inventive device is applicable to optics, optoelectronics, optical information recording, and liquid crystal display devices, and to various uses such as those of security and design, and is highly valuable in the industry.

5   [Best Mode of Carrying Out the Invention]

[0063]   The present invention will be further described with reference to the following examples but is not limited thereto.
[0064]   In the following examples, the measurement of inherent viscosity, the determination of liquid crystal series,
10   and the measurement of film thickness are conducted in accordance with the following methods .

(1) Measurement of inherent viscosity

[0065]   Measured in a mixed solvent of phenol and tetrachloroethane in a weight ratio of 60/40 at a temperature of
15   30°C using a ubbelohde's viscometer

(2) Determination of liquid crystalline phase

[0066]   Determined by DSC (differential scanning calorimeter) analysis using Perkin Elmer DSC-7 and observation
20   through an optical microscope, BH2 polarizing microscope manufactured by Olympus Optical Co., Ltd.

(3) Measurement of film thickness

[0067]   Measured using a surface texture analysis system Dektak 3030ST manufactured by ULVAC Inc. Also used
25   a method of obtaining the film thickness from the interference wave measurement with a ultraviolet, visible and near-infrared spectrophotometer V-570 manufactured by JASCO Corporation and data from index of refraction.

Example 1

30   [0068]   A liquid crystalline polyester was prepared by melt-polymerizing 200 mmol dimethyl biphenyl-4,4'-dicarbox-ylate, 120 mmol (S)-2-methyl-1,4-butanediol (enantiomeric excess, e. e. = 50.0%), and 80 mmol 1,6-hexanediol using tetra-n-butyl orthotitanate at a temperature of 220 °C for 2 hours. The inherent viscosity of the resulting polyester was 0.18 dL/g.
[0069]   A tetrachloroethane solution of 10 weight percent of the resulting polyester was prepared and spin-coated on
35   a polyphenylene sulfide substrate with a rubbed polyimide film, followed by removal of the solvent on a hot plate at a temperature of 60 °C. After the substrate was heated in an oven at a temperature of 180 °C for 10 minutes so as to be oriented in a smectic A phase, it is cooled to a temperature of 120 °C at which it is oriented so as to assume a smectic C phase, at a rate of 4 °C/minute. The substrate was taken out from the oven and cooled to room temperature thereby fixing the orientation of the liquid crystalline polymer so as to be in a glass state (Sample 1). The resulting
40   liquid crystal layer was transferred to a triacetyl cellulose film with an adhesive thereby obtaining Sample 2.
[0070]   The liquid crystal layer in Sample 2 was glass-fixed, assuming a chiral smectic C phase having a helical structure and uniform in film thickness (1.1 μm). The polarizing microscope observation and the cross section electron microscope observation confirmed that the helical pitches of the helical structure of the liquid crystal layer in Sample 2 were about 1.0 μm. It was also found that the helical axes directions did not conform with the rubbing direction and
45   was offset therefrom at an angle of about 10 ° in the anti-clockwise direction.
[0071]   A commercially available embossed film J52,989 manufactured by Edmond Scientific Japan Co., Ltd. was cut into such a rectangle piece of 20 cm x 15 cm that the diffraction direction of the diffraction grating was the direction of the long side and then superposed on Sample 2 such that the liquid crystal layer thereof was in contact with the diffraction grating surface. The helical axes direction of Sample 2 was approximately perpendicular to the grating di-
50   rection of the diffraction grating. One shorter side of the embossed film was then fixed to Sample 2 with a cellophane tape and inserted through a thermolaminating apparatus DX-350 manufactured by Torami Co., Ltd. so that the shorter side was the head end. The thermolamination was carried out at a laminating roll temperature of 75 °C, and the speed of travel of the sample was 25 mm per second. After thermolaminating, Sample 2 and the embossed film were in close contact with each other in one body. The resulting laminate was cooled to room temperature, and the film was gently
55   removed from Sample 2 . It was found that the liquid crystal layer remaining on the triacetyl cellulose substrate was fixed in the helical orientation state of a smectic liquid crystal, and had the uneven pattern transferred from the embossed film thereby obtaining Sample 3.
[0072]   When a light was vertically made incident upon the surface of Sample 3, a diffraction occurred in the helical

8

direction at a diffraction angle of about 40 ° and also a diffraction resulting from the uneven pattern of the embossed film occurred perpendicularly to the helical axes at a diffraction angle of 35° . Therefore, it is confirmed that Sample 3 functioned as the complex diffraction device of the present invention.

5

Example 2

[0073]   The same procedures of Example 1 were followed except that the helical axes were approximately parallel to the grating direction of the embossed film thereby obtaining Sample 4.

[0074]   When a light was vertically made incident upon the surface of Sample 4, a diffraction occurred in the helical
10   direction at a diffraction angle of about 40 ° and also a diffraction resulting from the uneven pattern of the embossed film occurred parallel to the helical axes at a diffraction angle of 35° . Therefore, it is confirmed that Sample 4 functioned as a complex diffraction device of the present invention.
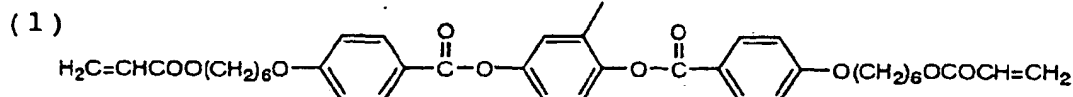
Example 3
15

[0075]   Sample 1 was subjected to the same embossing processing as that of Example 1. Thereupon, Sample 1 was laminated on the embossed film such that the helical axes direction were offset from the grating direction of the embossed film at an angle of about 30° . The resulting liquid crystal layer with the uneven pattern formed on the polyphenylene sulfide substrate was transferred to a triacetyl cellulose film with an adhesive thereby obtaining Sample 5. The
20   liquid crystal surface of Sample 5 was subjected to the same embossing processing again. Thereupon, the embossed film was arranged such that the grating direction was offset from the helical axes of Sample 5 at an angle of about 30° in the reverse side from the first embossing site thereby obtaining Sample 6.
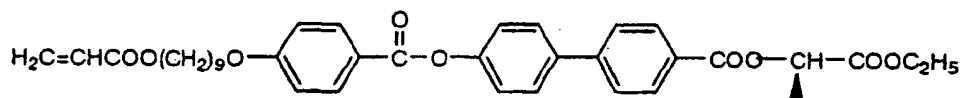
[0076]   When a light was vertically made incident upon the surface of Sample 6, a diffraction occurred in the helical direction at a diffraction angle of about 40 ° and also a diffraction resulting from the uneven pattern of the embossed
25   film occurred at a diffraction angle of 35° in the direction of about ±30° with respect to the helical axes direction. Therefore, it is confirmed that Sample 6 functioned as the complex diffraction device of the present invention.
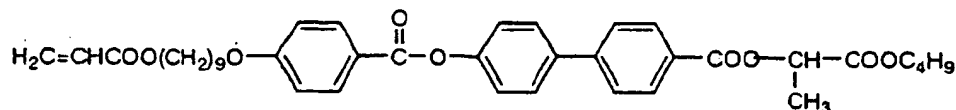
Example 4

30   [0077]

(1)

$$H_2C=CHCOO(CH_2)_6O-\langle\bigcirc\rangle-\overset{O}{\overset{\|}{C}}-O-\langle\bigcirc\rangle-O-\overset{O}{\overset{\|}{C}}-\langle\bigcirc\rangle-O(CH_2)_6OCOCH=CH_2$$

(2)

$$H_2C=CHCOO(CH_2)_9O-\langle\bigcirc\rangle-\overset{O}{\overset{\|}{C}}-O-\langle\bigcirc\rangle-\langle\bigcirc\rangle-COO-CH-COOC_2H_5$$

(3)

$$H_2C=CHCOO(CH_2)_9O-\langle\bigcirc\rangle-\overset{O}{\overset{\|}{C}}-O-\langle\bigcirc\rangle-\langle\bigcirc\rangle-COO-\underset{\overset{|}{CH_3}}{CH}-COOC_4H_9$$

[0078]   There was prepared a γ-butyrolactone solution containing 15 percent by mass of a mixture of a bifunctional
55   low molecular weight liquid crystal represented by the above formula (1), a mono-functional chiral liquid crystal represented by the above formula (2), and a racemic mono-functional liquid crystal represented by formula (3) mixed at a weight ratio of 10:80:10, 0.2 percent by mass of Irugacure 907 manufactured by Ciba Speciallity Chemicals Co. used as a photo-polymerization initiator, 0.02 percent by mass of KAYACURE DETX manufactured by Nippon Kayaku Co. ,

Ltd. as a sensitizer, and 0.05 percent by mass of Megaface F-144D manufactured by Dai Nippon Ink and Chemicals Inc as a surfactant.

[0079] The resulting solution was spin-coated on a rubbing-treated polyethylene terephthalate (PET) substrate, and the solvent was removed at a temperature of 60°C. After the substrate was then heated at a temperature of 100 °C in an oven for 3 minutes so as to be oriented in a smectic A phase, it was cooled to a temperature of 60 °C, at which it is oriented in a smectic C phase, at a rate of 5 °C per minute and maintained at a temperature of 60 °C for 3 minutes. Thereupon, nitrogen-substitution was done so as to make the oxygen concentration 3 percent by volume or less. Thereafter, the orientation of the liquid crystalline material was fixed by a photo-polymerization at an irradiation energy of 200 mJ/cm² using an ultraviolet irradiation device having a high-pressure mercury lump of 120 W/cm while maintaining a temperature of 60 °C. The resulting liquid crystal layer on the PET substrate was fixed, assuming a chiral smectic C phase having a helical structure and uniform in film thickness (1.2 μm). The polarizing microscope observation and the cross section electron microscope observation confirmed that the helical pitches of the helical structure of the liquid crystal layer were about 1.3 μm. It was also found that the helical axes direction did not conform with the rubbing direction and was offset at an angle of about 13 ° in the anti-clockwise direction thereby obtaining Sample 7.

[0080] Similarly to Example 1, Sample 7 was laminated on the embossed film at a temperature of 55°C. Thereafter, Sample 7 with the embossed film laminated was further subjected to a light irradiation of 800 mJ thereby curing the liquid crystal layer completely. The embossed film was removed from the liquid crystal layer thereby obtaining Sample 8.

[0081] When a light was vertically made incident upon the surface of Sample 8, a diffraction occurred in the helical direction at a diffraction angle of about 29 ° and also a diffraction resulting from the uneven pattern of the embossed film occurred perpendicularly to the helical axes at a diffraction angle of 35° . Therefore, it is confirmed that Sample 8 functioned as the complex diffraction device of the present invention.

Example 5

[0082] A liquid crystalline polyester was prepared by melt-polymerizing 200 mmol dimethyl biphenyl-4,4'-dicarboxylate, 80 mmol (R)-1,3-butanediol (enantiomeric excess, e. e. = 95.0%), and 120 mmol 1,5-pentane diol using tetra-n-butyl orthotitanate at a temperature of 220 °C for 2 hours. The inherent viscosity of the resulting polyester was 0.20 dL/g.

[0083] An N-methyl-2-pyrrolidone solution of 10 percent by mass of the resulting polyester was prepared and spin-coated on a rubbing-treated PET film substrate, followed by removal of the solvent on a hot plate at a temperature of 60 °C. After the substrate was heated in an oven at a temperature of 120 °C for 10 minutes, it was taken out therefrom and cooled to room temperature so as to fix the orientation of the liquid crystalline polyester in a glass state, thereby obtaining Sample 9.

[0084] The liquid crystal layer in Sample 9 was glass-fixed, assuming a chiral smectic C_A phase with a helical structure and uniform in film thickness (1.2 μm). The polarizing microscope observation and the cross section electron microscope observation confirmed that the helical pitches of the helical structure of the liquid crystal layer in Sample 9 were about 0.8 μm.

[0085] Similarly to Example 1, Sample 9 was laminated on the embossed film at a temperature of 75°C thereby obtaining Sample 10.

[0086] When a light was vertically made incident upon the surface of Sample 10, a diffraction occurred in the helical direction at a diffraction angle of about 52 ° and also a diffraction resulting from the uneven pattern of the embossed film occurred perpendicularly to the helical axes at a diffraction angle of 35° . Therefore, it is confirmed that Sample 10 functioned as the complex diffraction device of the present invention.

Claims

1. A complex diffraction device wherein a diffraction function resulting from an uneven pattern is added to a diffraction device comprising a liquid crystal layer where the helical orientation of the smectic liquid crystalline phase having a helical structure is maintained.

2. A complex diffraction device wherein a diffraction function resulting from an uneven pattern is added to one or both surfaces of a diffraction device comprising a liquid crystal layer where the helical orientation of the smectic liquid crystalline phase having a helical structure is maintained.

3. The complex diffraction device according to Claim 1 or 2 wherein the diffraction direction and/or angle of the diffraction device comprising a liquid crystal layer where the helical orientation of the smectic liquid crystalline phase having a helical structure is maintained are different on at least a part of the device from those of a diffraction

resulting from the uneven pattern.

4. The complex diffraction device according to Claim 1, 2 or 3 wherein said liquid crystal layer is formed by orienting a thin film of a liquid crystalline material which can exhibit a helical-structured smectic liquid crystalline phase, at a temperature which is the glass transition temperature or higher and cooling it to be in a glass state so as to fix the helical structure of the smectic liquid crystalline phase formed in the film layer.

5. The complex diffraction device according to Claim 1, 2 or 3 wherein said liquid crystal layer is formed by orienting a thin film of a liquid crystalline material which can exhibit a helical-structured smectic liquid crystalline phase at a temperature at which the liquid crystalline material exhibits the liquid crystalline phase, and polymerizing the liquid crystalline material with the orientation maintained so as to fix the helical structure of the smectic liquid crystalline phase formed in the film layer.

6. The complex diffraction device according to Claim 1, 2 or 3 wherein the helical structured smectic liquid crystalline phase formed in the liquid crystal layer is a chiral smectic C phase.

7. The complex diffraction device according to Claim 1, 2 or 3 wherein the helical structured smectic liquid crystalline phase formed in the liquid crystal layer is a chiral smectic C_A phase.

8. A method of producing a complex diffraction device wherein a liquid crystal layer where the helical structure of a smectic liquid crystalline phase is prepared from a liquid crystalline material exhibiting a smectic liquid crystalline phase with a helical structure, and then the liquid crystal layer surface is subjected to an embossing processing so as to provide a diffraction function resulting from an uneven pattern.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP00/06551

A. CLASSIFICATION OF SUBJECT MATTER

Int.Cl⁷   G02B5/18, G02B5/30, C08F20/30

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Int.Cl⁷   G02B5/18, G02B5/30, C08F20/30

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho	1926-1996	Toroku Jitsuyo Shinan Koho	1994-2000
Kokai Jitsuyo Shinan Koho	1971-2000	Jitsuyo Shinan Toroku Koho	1996-2000

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	WO, 99/34242, A1 (NIPPON OIL COMPANY, LTD.), 08 July, 1999 (08.07.99), Full text; all drawings & EP, 1045260, A1	1,2,4-6,8 3,7
A	Japanese Journal of Applied Physics, Vol.21, No.2, February,1982, Katsumi KONDO, et al, "Temperature Sensitive Helical Piches and Wall Anchoring Effects in Homogeneous Monodomains of Ferroelectric Sm C* Liquid Crystals, nOBAMBC(n=6-10)", P224-229	1-6
PY	JP, 2000-89216, A (Mitsubishi Oil Co., Ltd.), 31 March, 2000 (31.03.00), Full text; all drawings (Family: none)	1-8
PY	JP, 2000-89015, A (Mitsubishi Oil Co., Ltd.), 31 March, 2000 (31.03.00), Full text; all drawings (Family: none)	1-8
Y	JP, 11-60972, A (NIPPON OIL COMPANY, LTD.), 05 March, 1999 (05.03.99) & US, 6068792, A	1-8

☒ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

*	Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	
"E"	earlier document but published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	
"P"	document published prior to the international filing date but later than the priority date claimed	"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 December, 2000 (12.12.00)	19 December, 2000 (19.12.00)

Name and mailing address of the ISA/ Japanese Patent Office	Authorized officer
Facsimile No.	Telephone No.

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP00/06551

C (Continuation).   DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP, 4-107504, A (TOPPAN PRINTING CO., LTD.), 09 April, 1992 (09.04.92), Full text; all drawings (Family: none)	1-8
Y	JP, 11-72619, A (Sekisui Chemical Co., Ltd.), 16 March, 1999 (16.03.99), Full text; all drawings (Family: none)	1-8
Y	JP, 3-129382, A (Dainippon Printing Co., Ltd.), 03 June, 1991 (03.06.91), Full text; all drawings (Family: none)	1-8

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

(54) Abstract Title
   Optical waveguide Bragg grating system

(57)   An optical waveguide Bragg grating system has a length of optical waveguide 2 containing a set of Bragg gratings at each of a number of locations 10, 20, 30. Each location is assigned a unique digital code defining the wavelength set of the gratings at that location. The Bragg grating locations may be mechanical-strain sensing locations. For sensing, the waveguide 2 is coupled to a broadband optical source 5 and the combined response from all the grating locations 15 is correlated 16 with each digital code to discriminate responses from the respective grating locations. In an alternative arrangement, a communication system uses a plurality of sources of unique wavelength and reflective taps at each grating location.
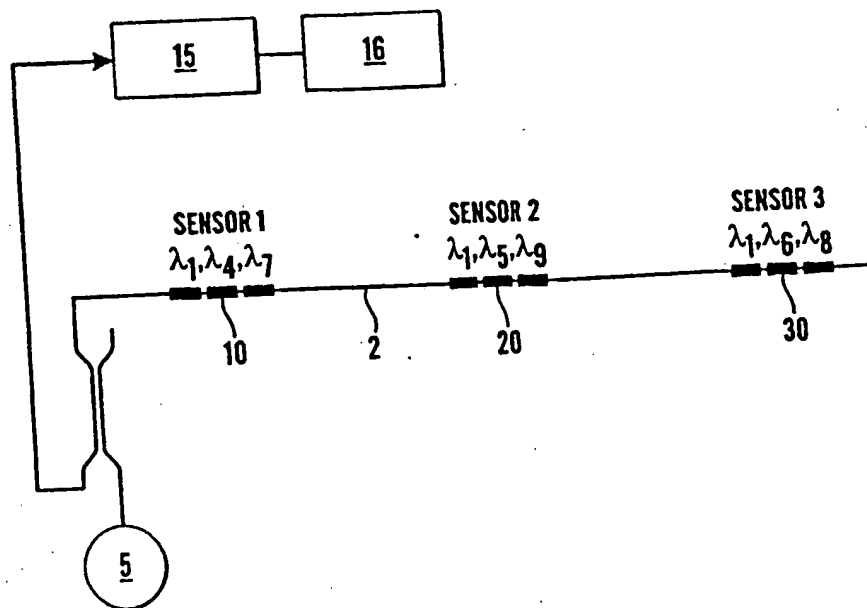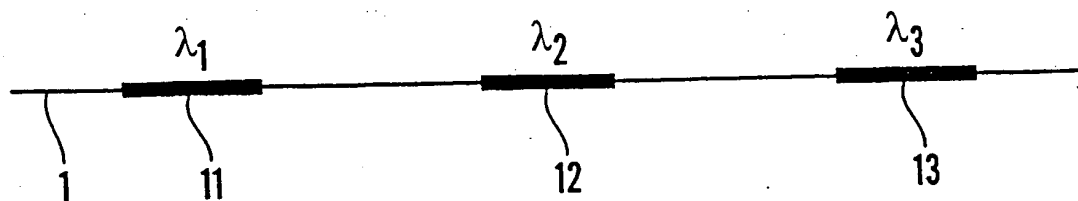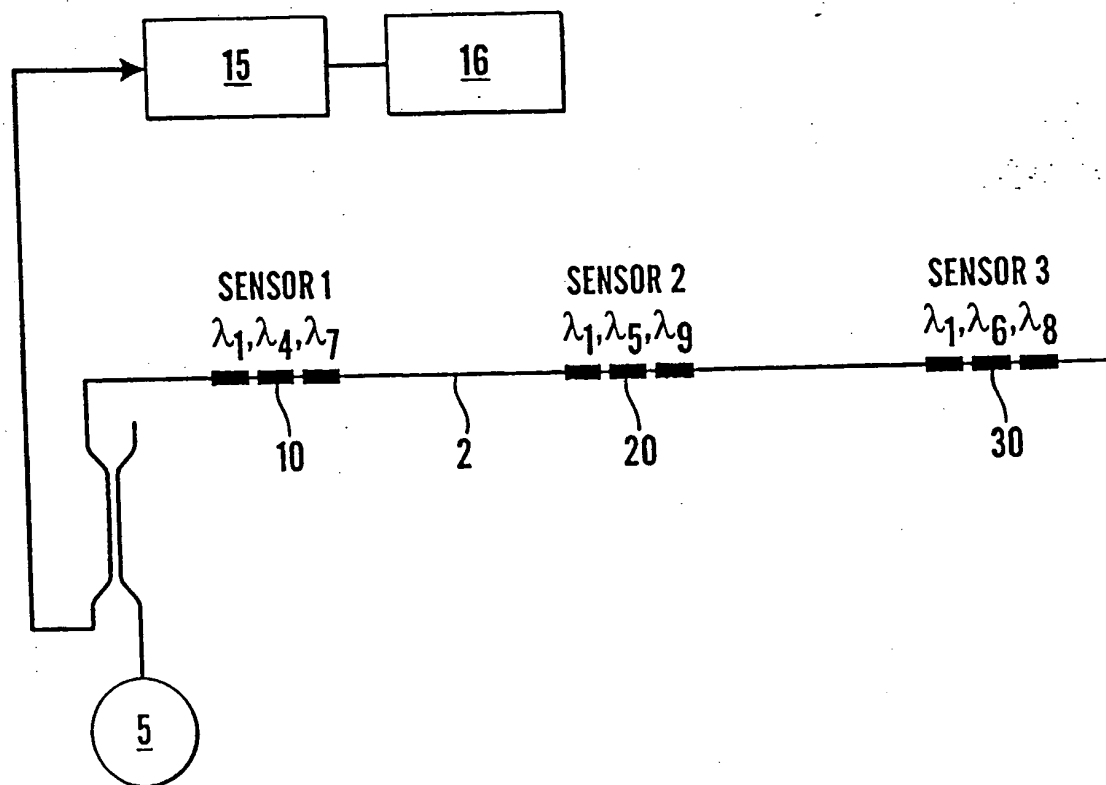

Fig.1(b)

GB 2 372 100 A

λ_1 λ_2 λ_3

1 11 12 13

Fig. 1(a)

15 16

SENSOR 1
$\lambda_1, \lambda_4, \lambda_7$

SENSOR 2
$\lambda_1, \lambda_5, \lambda_9$

SENSOR 3
$\lambda_1, \lambda_6, \lambda_8$

10 2 20 30

5

Fig. 1(b)

Fig.2

SENSOR 1
SENSOR 2
SENSOR 3

1	0	0	1	0	0	1	0	0
1	0	0	0	1	0	0	0	1
1	0	0	0	0	1	0	1	0

CODE 1

CODE 2

CODE 3

CODE 1 (THRESHOLDED)

CODE 2 (THRESHOLDED)

CODE 3 (THRESHOLDED)

Fig.3

SENSOR 1	1	0	1	0	0	1	0	0		
SENSOR 2		1	0	0	1	0	0	1	0	
SENSOR 3			1	0	0	0	1	0	1	0

CODE 3

CODE 2

CODE 1

CODE 3 (THRESHOLDED)
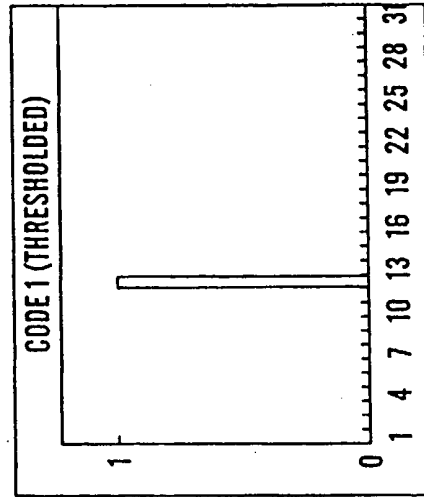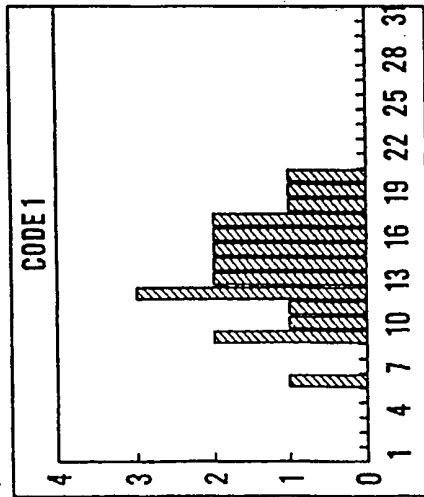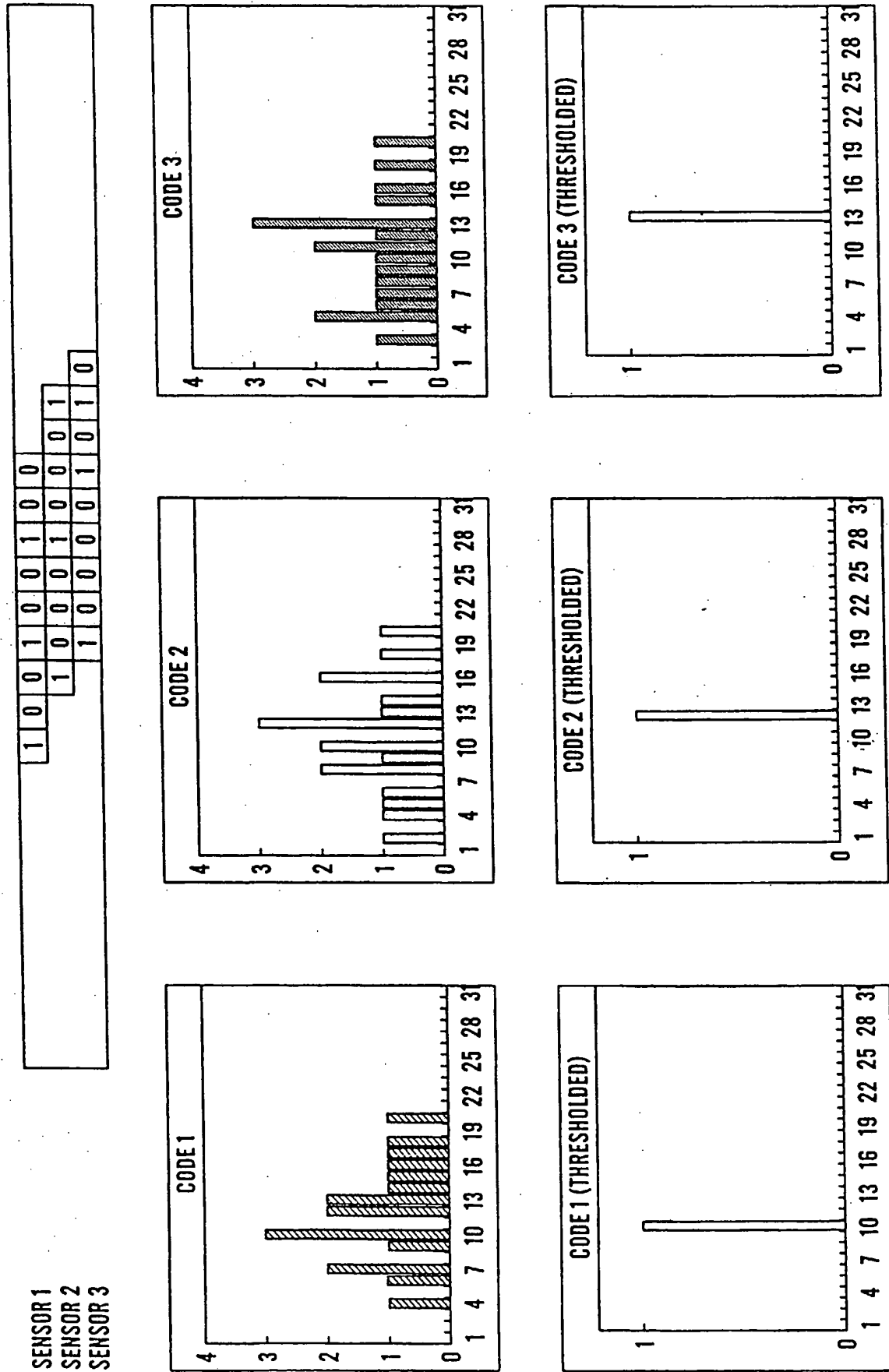
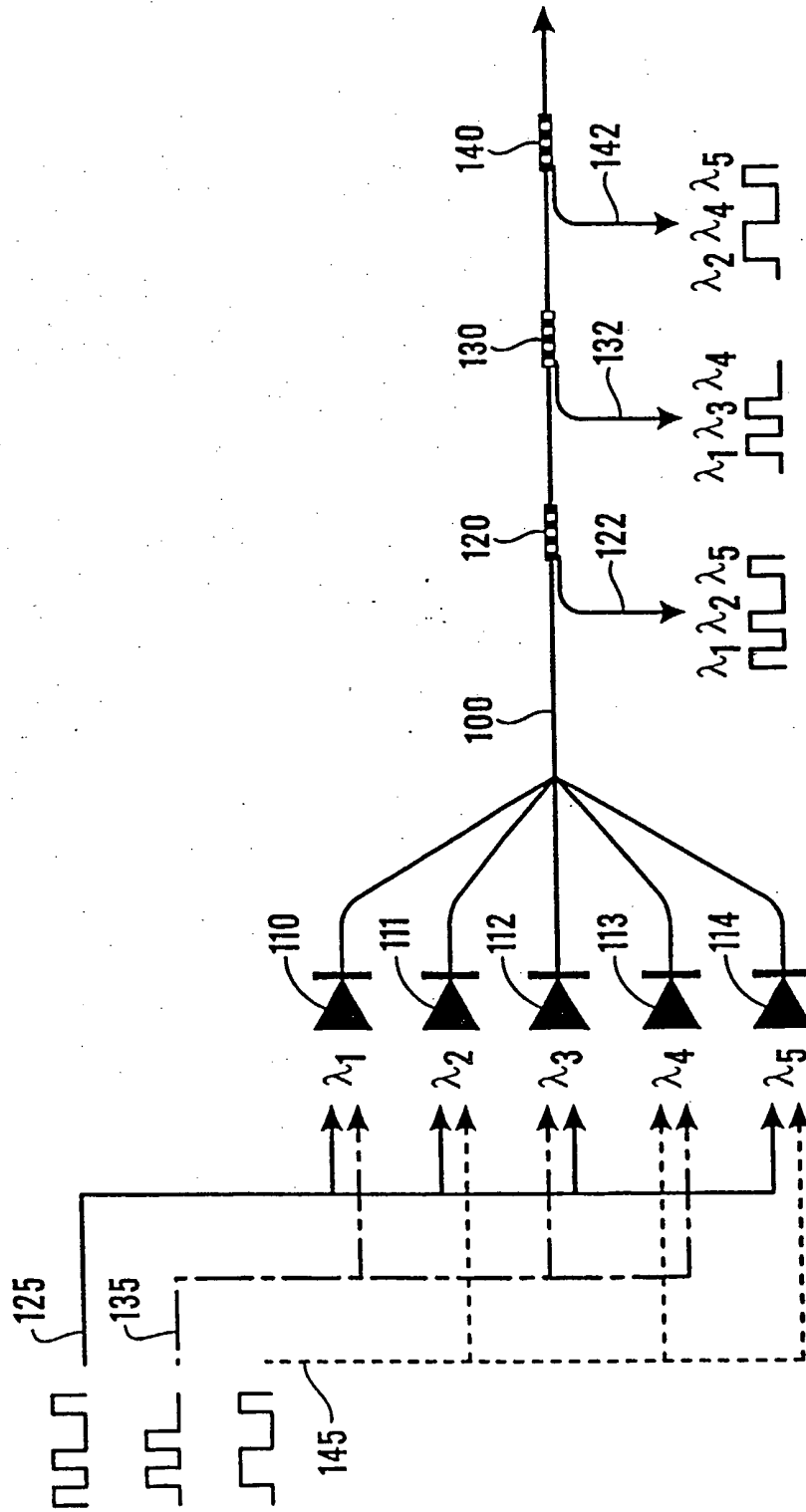CODE 2 (THRESHOLDED)

CODE 1 (THRESHOLDED)

Fig.4

Fig.5

.1
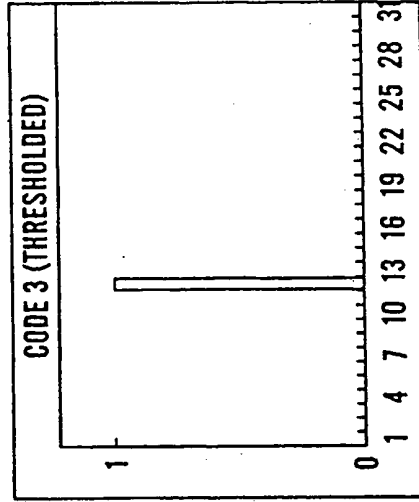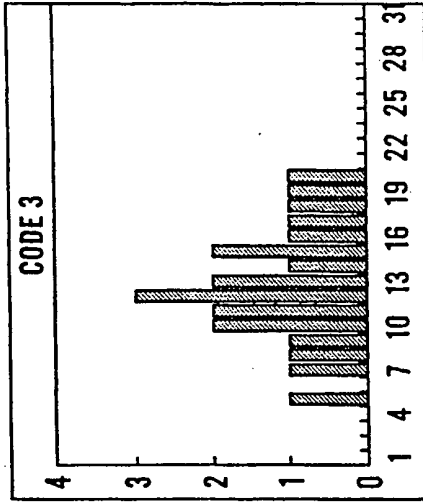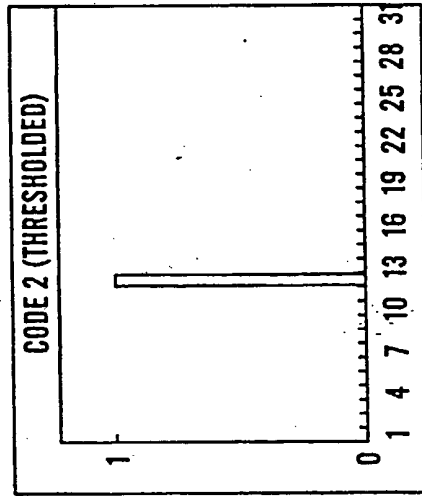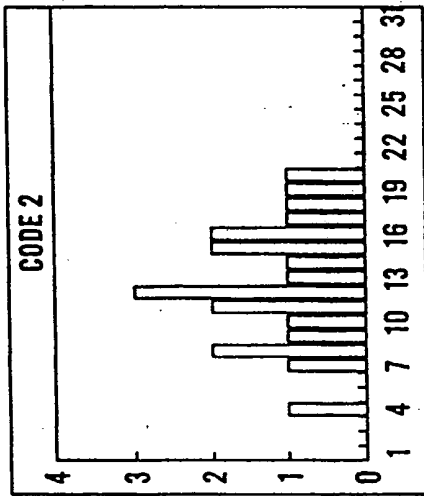
OPTICAL WAVEGUIDE BRAGG GRATING SYSTEM

This invention relates to an optical waveguide Bragg grating system and particularly, although not exclusively to a system utilising optical fibre Bragg gratings as sensors.

5   Optical waveguide Bragg gratings are finding increasing application as sensors, particularly of mechanical strain and other parameters, for example temperature, which can be represented in terms of induced strain.

10   A plurality of Bragg gratings can usefully be cascaded along the length of a single waveguide such as an optical fibre. In sensor applications, this usefully provides the ability to sense a parameter at the location of each grating in the series. In such an arrangement each sensor in the series has a unique wavelength response and the sensors are addressed by means of a single wideband optical source, the bandwidth of which covers the wavelength response range of all the sensors in a series. Analysing the reflected

15   response from all the sensors by means of a spectrum analyser enables the responses from individual sensors to be determined.

A cascaded Bragg grating system as described, has a significant limitation in the form of

20   the inevitable compromise, which has to be made between the number of gratings in the series, their required dynamic range and the optical bandwidth available from a single optical source.

This invention seeks to provide an optical waveguide Bragg grating system in which the

above-mentioned limitation is mitigated.

According to one aspect of the invention there is provided an optical waveguide Bragg grating system comprising a length of optical waveguide having a plurality of Bragg

5   grating locations spaced apart along its length, each grating location containing a plurality of superimposed Bragg gratings formed thereat, each of the superimposed gratings at a respective location having a characteristic response wavelength different from the other gratings at that location, each location being assigned a unique digital code defining a unique set of response wavelengths of the gratings at that location, an optical source for

10   providing an optical signal to the optical waveguide, the signal having a bandwidth which includes the response wavelength of each grating at each location, a correlator for correlating in wavelength space combined optical responses from all locations with each code, whereby the responses from each grating location may be uniquely determined.

15   The optical waveguide is preferably an optical fibre, typically single mode optical fibre.

A signal amplitude threshold circuit may be coupled to an output of the correlator to increase discrimination of the responses from the respective grating locations.

20   The digital codes assigned to the grating locations may be Prime Codes.

The Bragg grating locations may be mechanical strain-sensing locations, a change in the wavelength response from a respective location being indicative of a change in mechanical strain induced in the optical waveguide at that location.

According to a second aspect of the invention there is provided an optical Code Division Multiple Access (CDMA) data communications system comprising a length of optical fibre waveguide having a plurality of Bragg grating locations spaced apart along its length,

5   each grating location containing a plurality of superimposed Bragg gratings formed thereat, each of the superimposed gratings at a respective location having a characteristic response wavelength different from the other gratings at that location, each location being assigned a unique digital code defining a unique set of response wavelengths of the gratings at that location and having a respective reflective tap, a plurality of optical sources

10   coupled to the optical waveguide, each source having a unique respective wavelength corresponding to the characteristic response wavelength of a different respective one of the gratings at the plurality of Bragg grating locations, a data input for feeding data intended to be received at the reflective tap of a grating location to each optical source having a wavelength corresponding to the characteristic response wavelength of each grating at said

15   grating location and a correlator coupled to each reflective tap for correlating in wavelength space optical signals received at a respective tap with each digital code, whereby data signals intended for that tap may be discriminated.

The optical waveguide is preferably an optical fibre, typically single mode optical fibre.

20

A signal amplitude threshold circuit may be coupled to an output of each correlator to increase discrimination of the responses from the respective grating locations.

The digital codes assigned to the grating locations may be Prime Codes.

An exemplary embodiment of the invention will now be described with reference to the

drawings in which:

Fig.1 (a) shows a known Bragg grating system;

5

Fig. 1 (b) shows a preferred embodiment of a Bragg grating system in accordance with a

first aspect of the invention;

Figs.2, 3 and 4 illustrate results of correlation for three possible cases; and

10

Fig.5 shows a preferred embodiment of an optical CDMA data communications system in

accordance with a second aspect of the invention.

Referring now to Fig.1(a), there is shown a known optical waveguide Bragg grating system

15   in which a single mode optical fibre 1, has Bragg gratings 11, 12, and 13 of respective

characteristic reflection wavelengths λ_1, λ_2, λ_3 formed at intervals along its length. In this

example the gratings are provided as sensors for sensing, for example mechanical strain.

The gratings 11, 12 and 13 are typically addressed by means of a wide-band optical source

20   coupled to the fibre 1 and reflected responses from the grating sensors are analysed by

means of a spectrum analyser. A change in the spectral response of a grating sensor

indicates a change in the sensed parameter, in this case mechanical strain.

A problem with this arrangement is the compromise, which must be made between the

number of grating sensors, which may be cascaded in this way, their required dynamic range and the optical bandwidth available from a single source, to cover the range of characteristic reflection wavelengths of all the cascaded gratings. In a typical strain sensing application, it is possible to support eight cascaded Bragg grating sensors, each having a wavelength window 5nm wide, equivalent to a strain-response range of 0-3000μstrain, within the typical 40nm spectral range of state-of-the-art semiconductor diode sources.

In seeking to mitigate this problem, the present invention draws on techniques from the field of Code Division Multiple Access, (CDMA) communications to provide resolution of the responses from optical waveguide Bragg gratings.

In a typical CDMA system, each bit is encoded into a waveform s(t) that corresponds to a code sequence of N chips representing the destination address of that bit. Each receiver correlates its own address $f(t)$ with the received signal $s(t)$. The received output $r(t)$ is:

$$(1)$$

$$r(t) = \int_{-\infty}^{\infty} s(z) \cdot f(z - t) \cdot dz$$

If the signal has arrived at the correct destination, then $s(t) = f(t)$ and Equation (1) represents an auto-correlation function. If the signal has arrived at an incorrect destination, then $s(t) \neq f(t)$ and (1) represents a cross-correlation function. At each receiver, to maximise the discrimination between the correct (destination) signal and interference (all other signals), it is necessary to maximise the auto-correlation function and to minimise the cross-correlation function. This is accomplished by selecting a set of orthogonal code

sequences. Optimum discrimination occurs for conditions under which the auto-correlation function is a maximum and the cross-correlation function is simultaneously a minimum. The size of the code applied to each transmitted bit depends on the number of receivers in the system. In a binary signalling scheme, this has a minimum size of 2^{N-1},

5   where N is the number of receivers involved, although optimum code design strategies may demand significantly longer codes.

In the present invention these principles are applied in a first aspect of the invention to discriminating responses from a set of Bragg grating locations spaced along a length of

10   optical waveguide and in a second aspect to provide an optical CDMA data system in which data signals intended for respective ones of a number of locations may be discriminated by means of Bragg gratings provided at those locations.

Referring to Fig.1 (b), there is shown a Bragg grating sensor system comprising an optical

15   waveguide in the form of a single mode optical fibre 2 provided with Bragg grating locations 10, 20, 30 at spaced intervals along its length. A wideband optical source 5 is coupled to feed the optical fibre 2 and signals reflected from each Bragg grating location 10, 20, 30 are fed to a spectrum analyser 15 and then to a correlator circuit 16.

20   Each Bragg grating location incorporates three gratings each having its own respective characteristic wavelength response, the set of three wavelengths at each grating location being unique to that location and hence different from the wavelength response set of any other grating location.

Each grating location 10, 20, 30 is assigned a digital code which defines in wavelength space the characteristic wavelength response of the three gratings at the respective location. Suitable code sequences are Prime Codes. These were initially developed as codes applicable to optical systems, giving better correlation properties in intensity-summation systems (i.e. in which the detected signal is always zero or positive) than the previous generation of codes (exemplified by Gold-sequences), which are more applicable to amplitude-detection. The following description is made with reference to Prime Codes, but the invention is not limited to such codes and any other suitable code sequence may be used.

For the system of Fig.1 (b), having three sensing sites, each with three gratings, the relevant Prime Codes are;

User	Code Sequence		
1	100	100	100
2	100	010	001
3	100	001	010

In this case Users 1, 2 and 3 represent the Bragg grating locations 10, 20, 30 and the code sequences represent the wavelengths of the characteristic wavelength responses of the three Bragg gratings at each location. Thus in a wavelength space covering nine different characteristic wavelengths of the code sequence, the gratings for user 1 at location 10 are

assigned wavelengths λ_1, λ_4 and λ_7, those at grating location 20 wavelengths λ_1, λ_5 and λ_9 and those at location 30 wavelengths λ_1, λ_6 and λ_8.

As described, a multiplicity of sensors share a common wavelength space and the potential

5 dynamic range, in wavelength terms, can therefore be much larger, since it is not necessary to prevent the dynamic wavelength excursions of one grating from encroaching on the spectral space allocated to its neighbours. In wavelength-space, therefore, the reflected response of a particular sensor comprises a number of delta-functions, forming a pattern unique to that sensor.

10

In order to discriminate the responses from the individual Bragg grating sensor locations, a spectral analysis is made of the sum of all grating sensor responses, taking no account of the positional origin of the signals received by the detection system consisting of the spectrum analyser 15 and the correlator 16. In the present example in which the Bragg

15 gratings at the three locations are functioning as strain sensors, as an individual sensing location experiences strain (or responds to an influence inducing strain) its characteristic coded response pattern shifts across the spectrum, modifying the integrated detected spectrum.

20 By performing, in correlator 16, a correlation in wavelength-space of the integrated detected spectral pattern against the specific sensor code, it is possible to assign the sensor response a position, which directly represents the induced shift in the wavelength pattern associated with the specific sensor location. With suitable choice of code patterns, the cross-correlation of the detected pattern associated with any particular sensor against the

codes of the remaining sensors in the set can be minimised, providing an unambiguous interrogation of any individual sensors in the set.

Referring now to Figs 2, 3 and 4 there are shown the output of the correlator 16 for three
5   cases. The first line of each Figure shows the raw results of autocorrelation, while the second row shows the same results after subjecting to thresholding.

In Fig.2, the nine-bit codes for each of the three sensor locations occupy non-overlapping positions in a 32-bin wavelength space. In this case all sensor locations are completely
10   resolved at positions 1, 12 and 23.
In Fig. 3, all three sensor locations are completely coincident in wavelength space, but as can be seen, the auto correlation with the respective codes discriminates each sensor response at position 12.

15   Similarly in Fig. 4, where sensor codes overlap in wavelength space, sensor outputs at positions 10, 12 and 13 are discriminated.

As can also be seen by thresholding the correlator output at signal magnitude slightly in excess of 2 on the vertical axis of each figure, the discrimination against unwanted signals
20   is considerable enhanced.

The above example has been described with reference to a nine bit code suitable for three sensor locations. The size of the code can be increased with a corresponding increase in the number of grating/sensing locations which may be supported and enhanced

discrimination between auto-correlation and cross-correlation functions.

The following is an example of the Prime codes for a five user/location system;

5

User	Code Sequence				
1	10000	10000	10000	10000	10000
2	10000	01000	00100	00010	00001
3	10000	00100	00001	01000	00010
4	10000	00010	01000	00001	00100
5	10000	00001	00010	00100	01000

The multiple Bragg gratings at each of the grating locations may be formed adjacent to each other, or to be superimposed one upon another. Such multiple gratings may be

10   formed by known techniques for forming Bragg gratings in optical fibres, such as, holographic exposure, phase mask exposure or direct writing into the fibre by optical beam.

In a second aspect, the invention may usefully be applied to provide an optical data

15   communications system. One exemplary embodiment is illustrated in Fig.5. In Fig. 5, an optical waveguide in the form of a single mode optical fibre 100 has coupled thereto five optical sources, typically laser diode sources, 110, 111, 112, 113 and 114, of respective wavelengths λ_1, λ_2, λ_3, λ_4, and λ_5.

At each of a plurality of locations, 120, 130 and 140 is provided a set of three Bragg gratings, those at location 120 having characteristic response wavelengths λ_1, λ_2, and λ_5, those at location 130 wavelengths λ_1, λ_3 and λ_4 and finally those at location 130 having

5   wavelengths λ_2, λ_4, and λ_5. Also at each grating location the fibre has a respective reflective tap 122, 132 and 142.

The optical sources 110 through 114 have data inputs 125, 135 and 145, for the supply of data intended to be received at the grating locations 120, 130 and 140 by way of the

10   reflective taps 122, 132 and 142. The data input 125, which carries data intended for reception by a user assigned to the tap 122, is coupled to drive the optical sources 110, 111 and 114, having wavelengths corresponding to the three wavelength responses of the gratings at the location 120. Similarly the data input 135 is coupled to the optical sources 110, 112 and 113 and the data input 145 to the sources 111, 113 and 114.

15

As with the embodiment described with respect to Fig. 1 (b) in conjunction with Figs. 2 to 4, a spectrum analyzer and correlator is coupled to each tap 122, 132, 142 and an auto correlation function is performed in wavelength space between the signals received at each of the taps and the digital codes assigned to the taps, in the manner described above. In

20   this way data intended to be transmitted to each of the users associated with each reflective tap along the optical fibre 100, may be discriminated.

The invention has been described by way of example and modifications may be made without departing from the scope of the invention. In particular, the invention is not

restricted to the use of optical fibre waveguides and any other suitable optical waveguide may be used, such as those formed using lithium niobate, III-V semiconductor and silica technologies. More than three gratings may also be employed at each location. The invention is also not restricted to the use of Prime Codes and any other suitable code structure may be employed. All that is required is that the digital code sequence chosen is suitable to support the number of gratings per location and the number of locations.

CLAIMS

1. An optical waveguide Bragg grating system comprising a length of optical waveguide having a plurality of Bragg grating locations spaced apart along its length, each grating location containing a plurality of superimposed Bragg gratings formed thereat, each of the superimposed gratings at a respective location having a characteristic response wavelength different from the other gratings at that location, each location being assigned a unique digital code representative of a unique set of response wavelengths of the gratings at that location, an optical source for providing an optical signal to the optical waveguide, the signal having a bandwidth which includes the response wavelength of each grating at each location, a correlator for correlating in wavelength space combined optical responses from all locations with each code, whereby the responses from each grating location may be uniquely determined.

2. The grating system of Claim 1 in which a signal amplitude threshold circuit is coupled to an output of the correlator to increase discrimination of the responses from the respective grating locations.

3. The grating system of Claim 1 or 2 in which the digital codes assigned to the grating locations are Prime Codes.

4. The grating system of any preceding claim in which the Bragg grating locations are mechanical strain-sensing locations, a change in the wavelength response from a respective location being indicative of a change in mechanical strain induced in the optical waveguide

at that location.

5.   An optical CDMA data communications system comprising a length of optical waveguide having a plurality of Bragg grating locations spaced apart along its length, each grating location containing a plurality of superimposed Bragg gratings formed thereat, each of the superimposed gratings at a respective location having a characteristic response wavelength different from the other gratings at that location, each location being assigned a unique digital code representative of a unique set of response wavelengths of the gratings at that location and having a respective reflective tap, a plurality of optical sources coupled to the optical waveguide, each source having a unique respective wavelength corresponding to the characteristic response wavelength of a different respective one of the gratings at the plurality of Bragg grating locations, a data input for feeding data intended to be received at the reflective tap of a grating location to each optical source having a wavelength corresponding to the characteristic response wavelength of each grating at said grating location and a correlator coupled to each reflective tap for correlating in wavelength space optical signals received at a respective tap with each digital code, whereby data signals intended for that tap may be discriminated.

6.   The system of Claim 5 in which a signal amplitude threshold circuit is coupled to an output of each correlator to increase discrimination of the responses from the respective grating locations.

7.   The system of Claim 5 or 6 in which the digital codes assigned to the grating locations are Prime Codes.

8.   The system of any preceding claim in which the optical waveguide is a length of optical fibre.

9.   The system of Claim 8 in which the optical fibre is single mode optical fibre.

10.   An optical waveguide Bragg grating system substantially as herein described with reference to and as shown in Figs 1 (b) and 2 to 4 of the drawings.

11.   An optical CDMA data communications system substantially as herein described with reference to and as shown in Fig. 5 of the drawings.

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Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

    UK Cl (Ed.S): G1A (ACA, ABF), H4B (BKX)

    Int Cl (Ed.7): G02B (6/34), H04J (14/02)

Other: Online: WPI, EPODOC, PAJ, INSPEC

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
	None	